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THE DEVELOPMENT AND TRAJECTORIES OF TORNADOES

By J. R. LLOYD

[U. S. Weather Bureau, Washington, March, 1942]

An excellent summary of the characteristic phenomena of the tornado, and an account of its genesis and development, are given by W. J. Humphreys in his treatise *Physics of the Air*, 3 ed., pp. 218–224. The main object of the present paper is to put on record an investigation of the synoptic data for two periods in March 1938 that completely substantiates the conception of the tornado proposed by Humphreys.

Figures 1, 2, and 3 show the surface synoptic situations at three different hours on March 15, 1938. The surface cold front associated with the LOW over central Kansas was accompanied by an upper-air cold front that preceded the surface front by from 75 to 100 miles or more. This upper front resulted from Marine Polar air overrunning Marine Tropical air; see figure 4.

As shown in figure 2, by 12:30 p. m., C. S. T., the cold front aloft had, at its northern end, begun to move forward over the cold air mass at the surface to the northward and northeastward of the center of the LOW; that is, this cold air mass was shallow and was being overrun by the Marine Tropical air from the south, while this overrunning Marine Tropical air was in turn being overrun from the south-southwest by subsiding Marine Polar air that originally came from the Pacific. There is a difference of around 30 percent between the dewpoints in the Marine Polar air over the western and central portions of Missouri, Arkansas and eastern Texas, and the dewpoints in the Marine Tropical air mass to the eastward.

Figure 5 shows the upper-air soundings from El Paso and Shreveport taken at 3 a. m., C. S. T. The sounding at Shreveport shows very moist Marine Tropical air with a stable lapse rate from the surface up to a marked temperature inversion at 5,200 feet, above which is found dry Superior air with a steep lapse rate. The air column at Shreveport is convectionally quite unstable. The sounding at El Paso indicates dry subsiding Marine Polar air with evidence of considerable stratification in the lower portions of the ascent. This air mass is considerably colder than the Marine Tropical mass to the eastward at Shreveport. As this Marine Polar air mass moved eastward and descended the eastern slopes of the Rocky Mountain plateau it heated adiabatically in the lower layers but remained considerably colder aloft than the Marine Tropical air to the eastward that it displaced.

Figure 6 shows the hourly progressions of the upper-air cold front, and of the six tornadoes that occurred on it. The second tornado, which occurred about 1:30 p. m. near McPaul in extreme southwestern Iowa, is of particular interest because it formed to the northward of the center of the LOW, in the surface cold sector, and moved from southeast to northwest. When its occurrence was reported to the Weather Bureau forecast center at Chicago, the writer (then stationed at that office) at once inferred that it must have moved from southeast to northwest; this deduction was based on the hypothesis that tornadoes develop on upper-air cold fronts and move up these fronts approximately at the speed of the wind in the warm sector of the cyclone just ahead of the upper-air cold front. The cold front aloft on which the McPaul tornado occurred then lay slightly north of west by slightly south of east, and in that locality was moving slowly northward with winds in the warm air ahead of it blowing from the east-southeast. The writer's deduction was later confirmed by the Weather Bureau section director of the State of Iowa in reply to a request for information on the McPaul tornado, as follows: "One of the most interesting things about this tornado, and it appears that it was truly a tornado, is the fact that it moved from southeast to northwest. I cannot recall any other such direction of tornado movement in Iowa." This section director had had many years of experience in that state prior to the occurrence of the McPaul tornado.

The trajectories of all the other tornadoes that occurred in connection with the upper-air cold front of March 15 were from southwest to northeast; the portion of the cold front on which these five tornadoes occurred lay generally north-south; the winds behind the cold front blew from a general westerly direction, and the winds ahead of the front blew from a general southerly direction. It should be noted particularly that the trajectory of the first tornado curved from due northeastward to northward in Illinois toward the end of its existence, corresponding to a change in the orientation of the upper-air cold front from a north-south direction, where the tornado originated, to a northwest-southeast direction.

Figures 7 to 12, inclusive, are corresponding charts for the conditions on March 30, 1938, when no fewer than 12 tornadoes occurred. On this occasion, the LOW centered over central Kansas, was accompanied by a surface cold front extending southward through Oklahoma and thence southwestward through western Texas, with an upper-air cold front curving southeastward to near Wichita and thence south-southwestward through central Texas, some 100 to 200 miles in advance of the surface front. The difference between the dewpoints in the Marine Polar air mass to the west of the cold front and in the Marine Tropical air mass to the eastward is even more marked than on the weather maps of March 15, and the tornadoes that occurred in connection with this cold front were more numerous and more violent. It will be noted in figure 10 that the winds in the Polar Pacific air mass are for the most part blowing directly from the west, while the winds in the Marine Tropical air mass in advance of the front are blowing from the south and southwest and at higher velocities.

The sounding from Shreveport, figure 11, shows very moist Marine Tropical air up to a temperature inversion at 5,400 feet, above which is found dry Superior air,

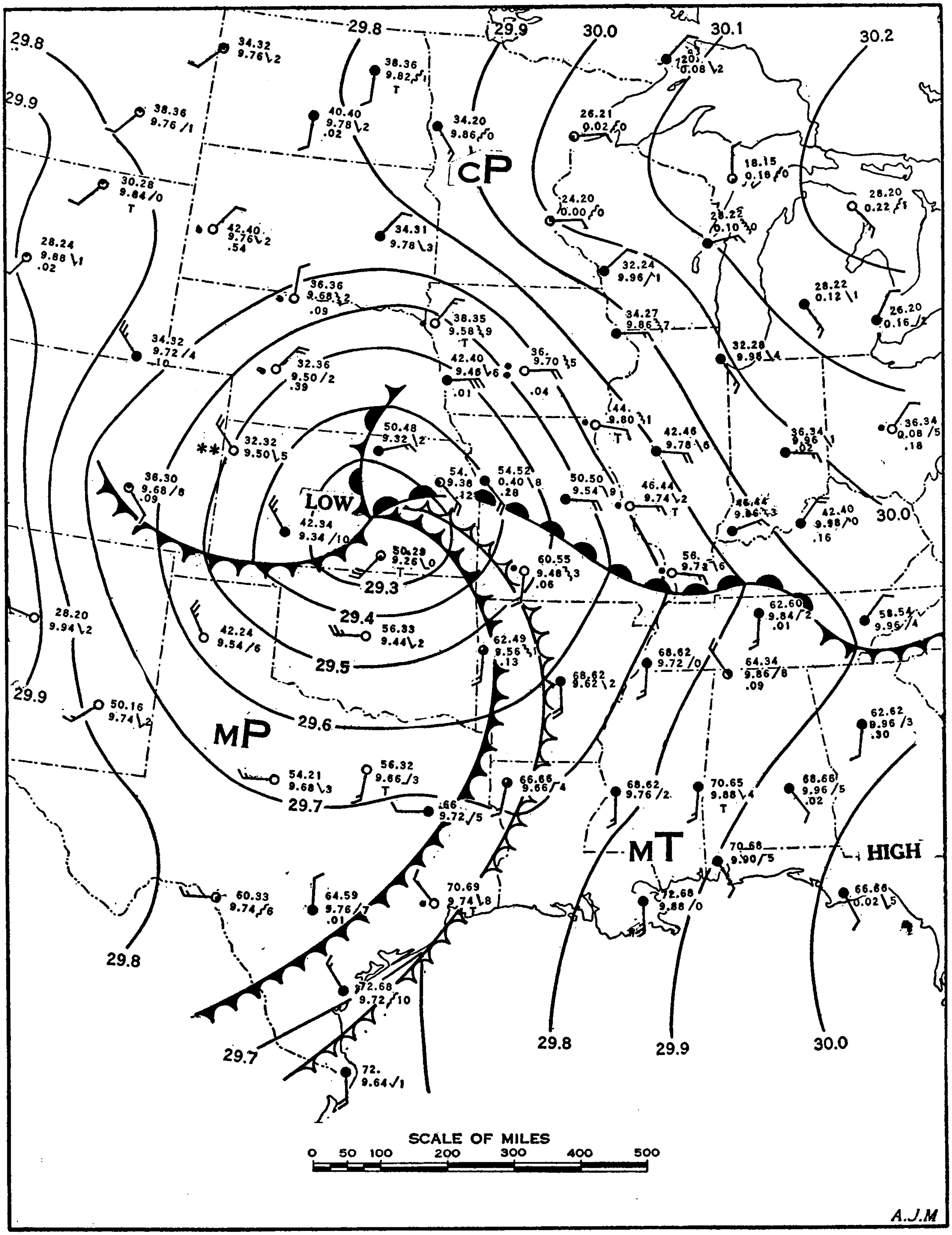

FIGURE 1.—Surface synoptic conditions, March 15, 1938, at 6:30 a. m., C. S. T.

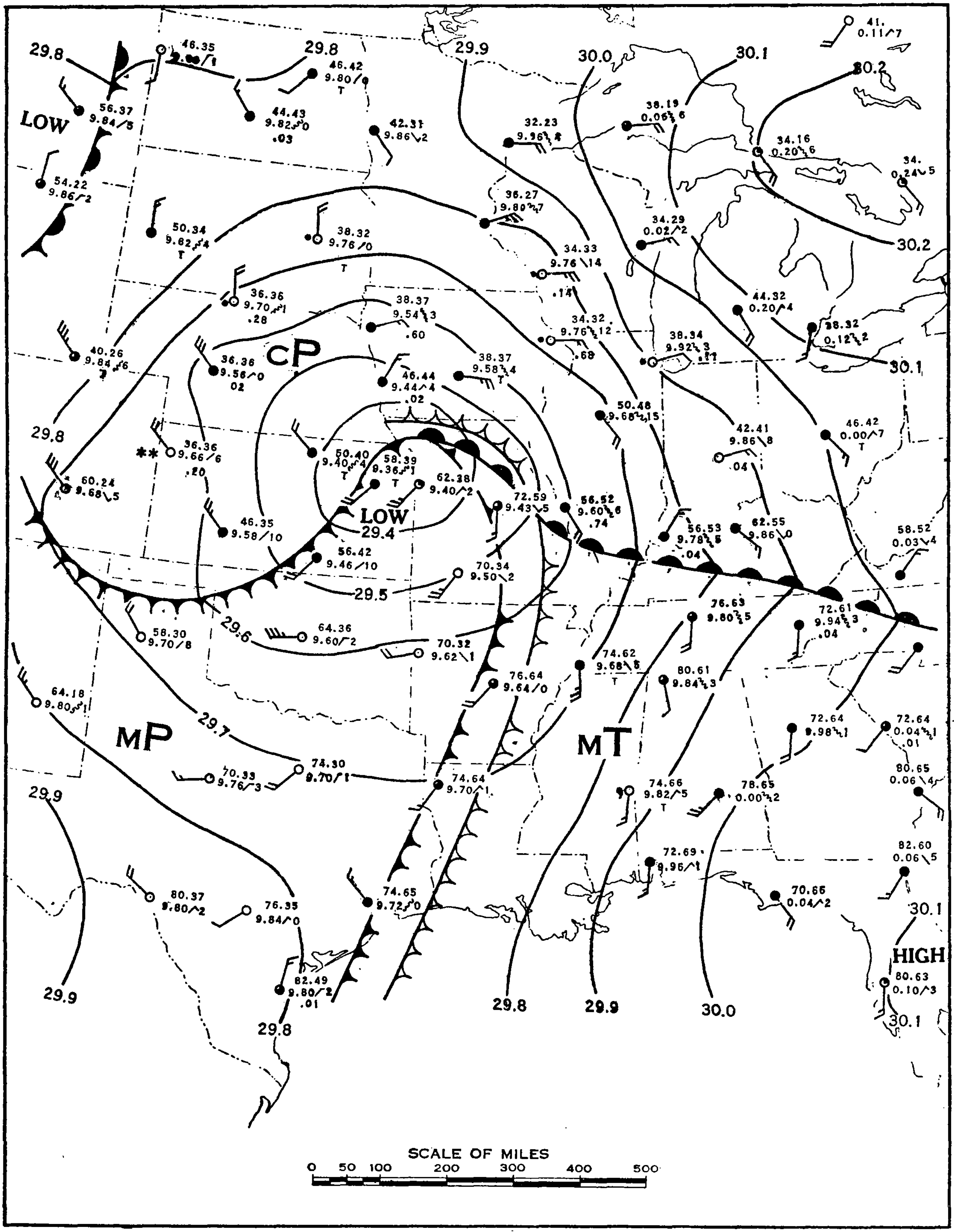

Figure 2.—Surface synoptic conditions, March 15, 1938, at 12:30 a. m., C. S. T.

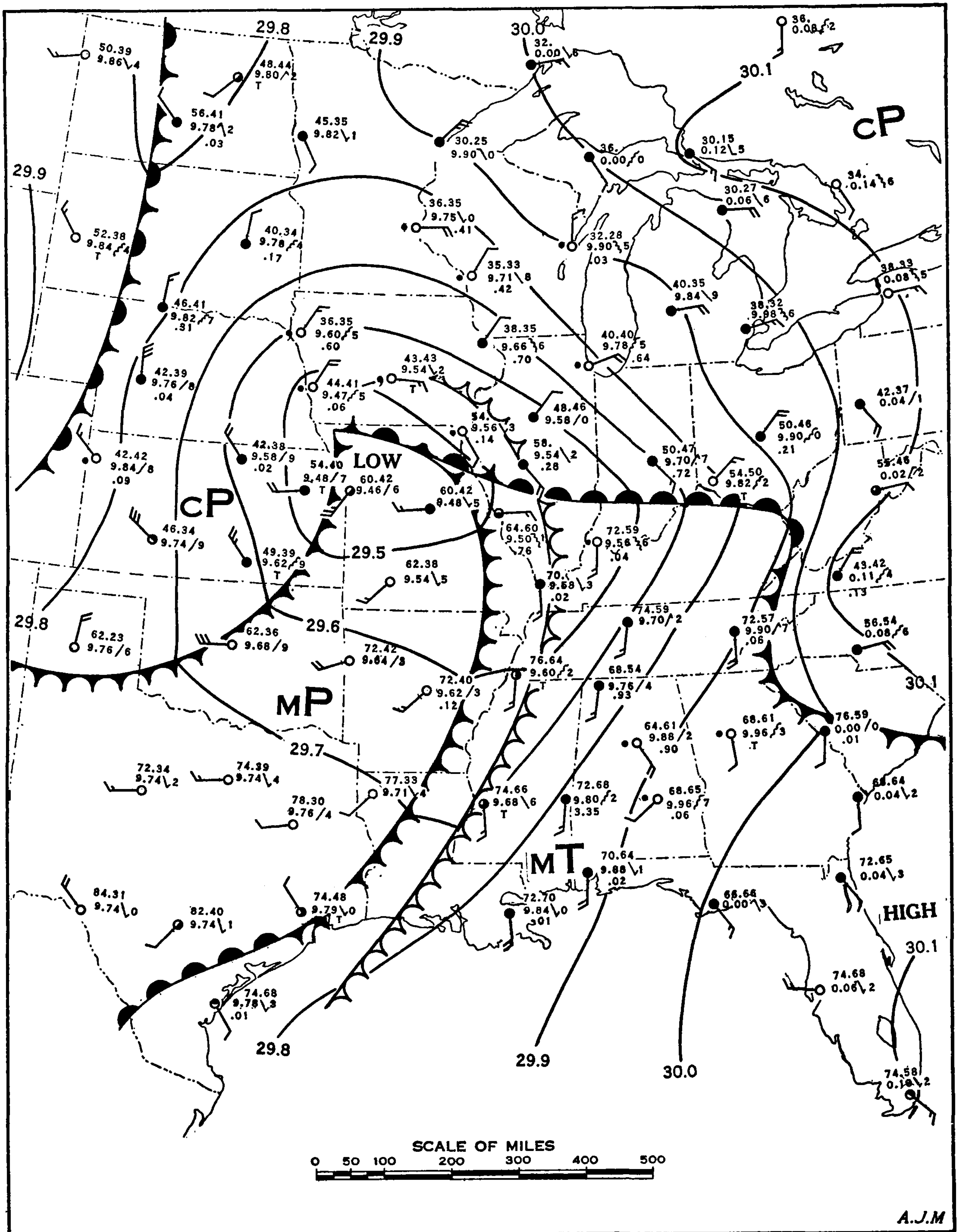

Figure 3.—Surface synoptic conditions, March 15, 1938, at 6:30 p. m., C. S. T.

similar to the condition at Shreveport on March 15; and the temperature inversion at the top of the Marine Tropical air mass is at approximately the same elevation. The sounding from El Paso shows dry subsiding Marine Polar air with a steep lapse rate in the lower half of the ascent, and the Marine Polar air was considerably colder than the

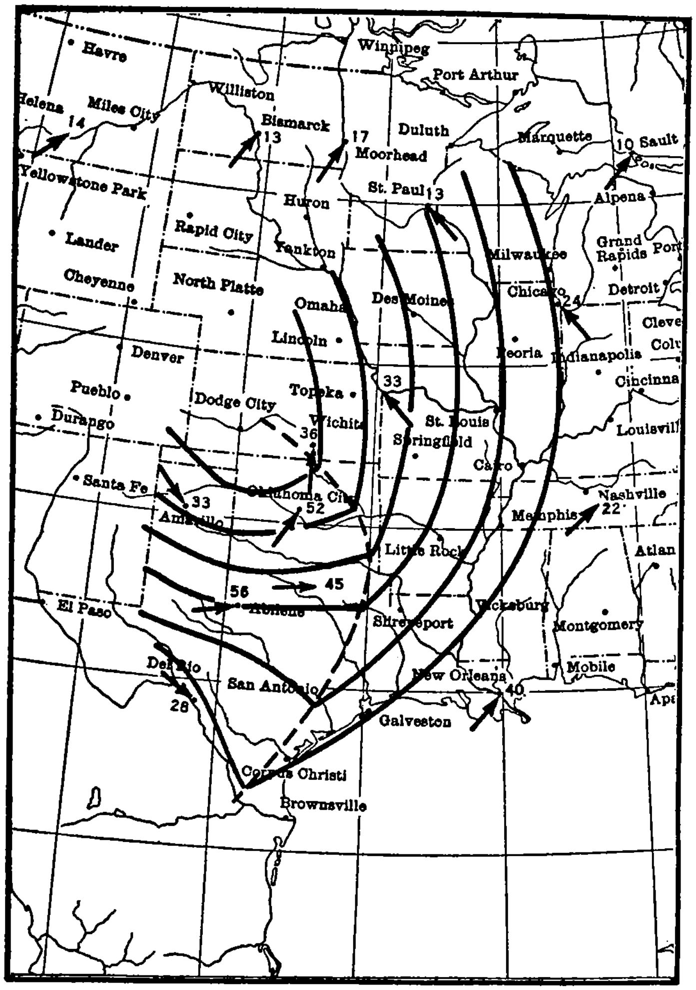

FIGURE 4.—Wind directions and speeds aloft at 4,000 feet, 4:00 a. m., C. S. T., March 15, 1938. Broken line indicates approximate position of upper-air cold front.

Marine Tropical air at Shreveport, as was also true on March 15. The sounding from Oklahoma City shows moist Marine Tropical air up to about the same height as the temperature inversion at Shreveport, above which is found dry air that is somewhat colder than the dry air above the temperature inversion at Shreveport. However, at Oklahoma City no temperature inversion is found between the Marine Tropical air mass and the dry air mass above it. On both March 15 and March 30 the Marine Tropical air mass was over-lain by a dry Superior air mass, an excellent setup for great convective instability under the action of a steep cold front.

All of the 12 tornadoes that occurred moved from southwest to northeast; in each case the cold front aloft lay in a general southwest-northeast direction, with the winds aloft in the Marine Polar air mass blowing from the west, and in the Marine Tropical air mass from the south or southwest.

Figure 13 shows a cross section through an ideal air mass system that is typical of the situations that occurred on March 15 and March 30. A mass of Marine Tropical air, domed up in the center, is overlain by a mass of Superior air. The eastern portion of the Marine Tropical air mass rests on the shoulder of a mass of transitional Polar air, and a mass of Marine Polar air that is changing

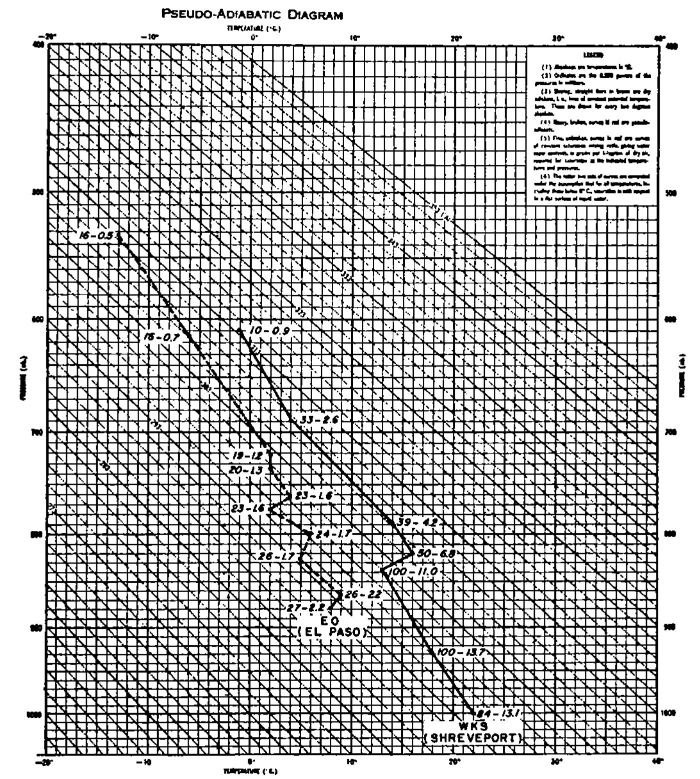

FIGURE 5.—Upper-air soundings from El Paso and Shreveport, 3:00 a. m., C. S. T. March 15, 1938.

to Superior air through the process of subsidence is encroaching on the Marine Tropical air mass from the west. The lower stratum of the subsiding Marine Polar

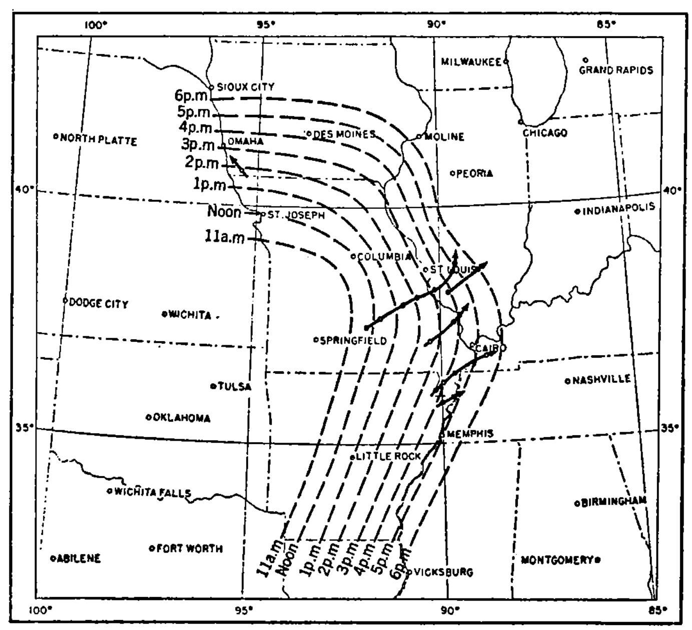

FIGURE 6.—Development and progression of the upper-air cold front and of the six tornadoes that occurred on it, March 15, 1938.

mass is somewhat warmer than the Marine Tropical mass that it is displacing, but the intermediate and upper strata of the subsiding Marine Polar air mass are consider-

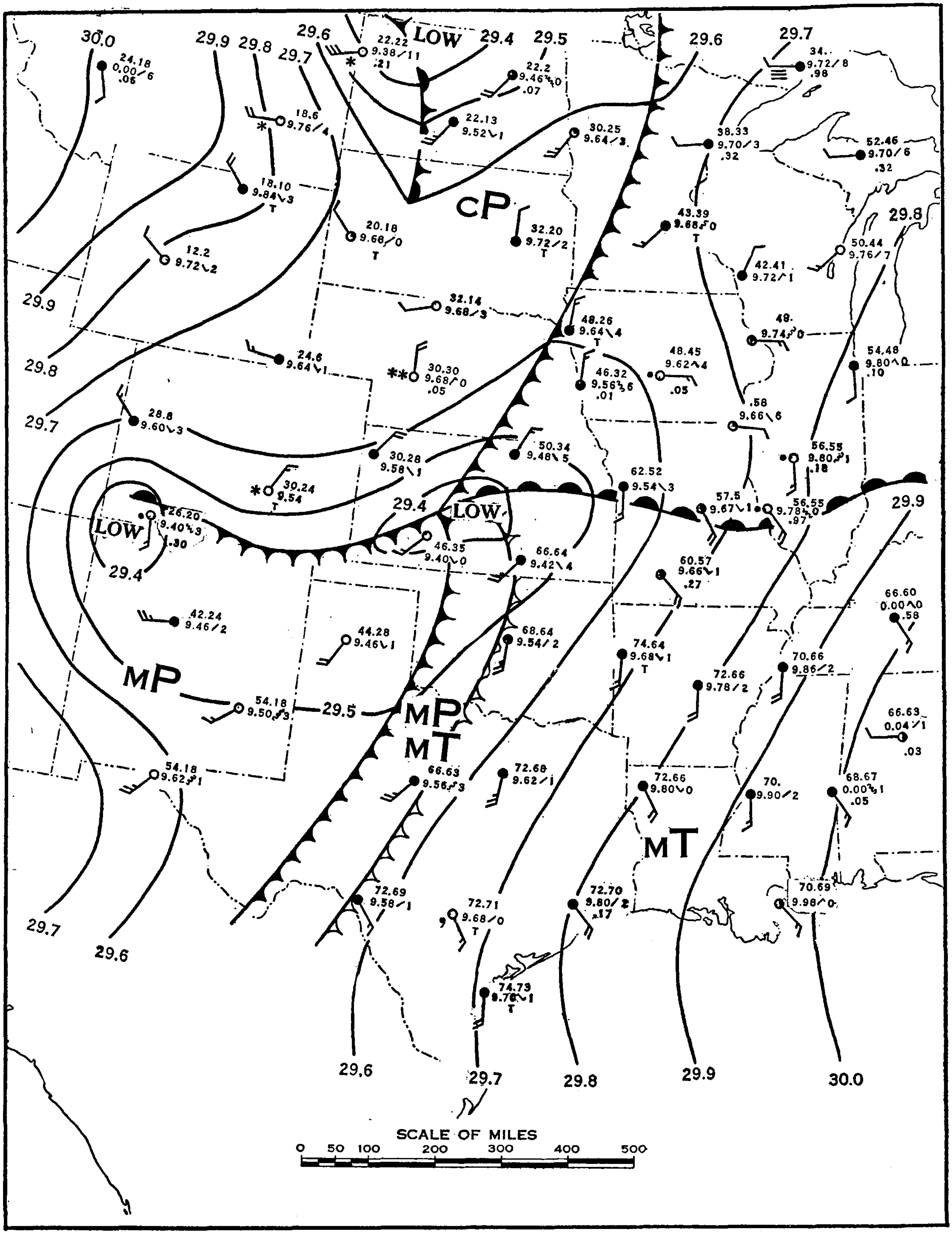

Figure 7.—Surface synoptic conditions, March 30, 1938, at 6:30 a. m., C. S. T.

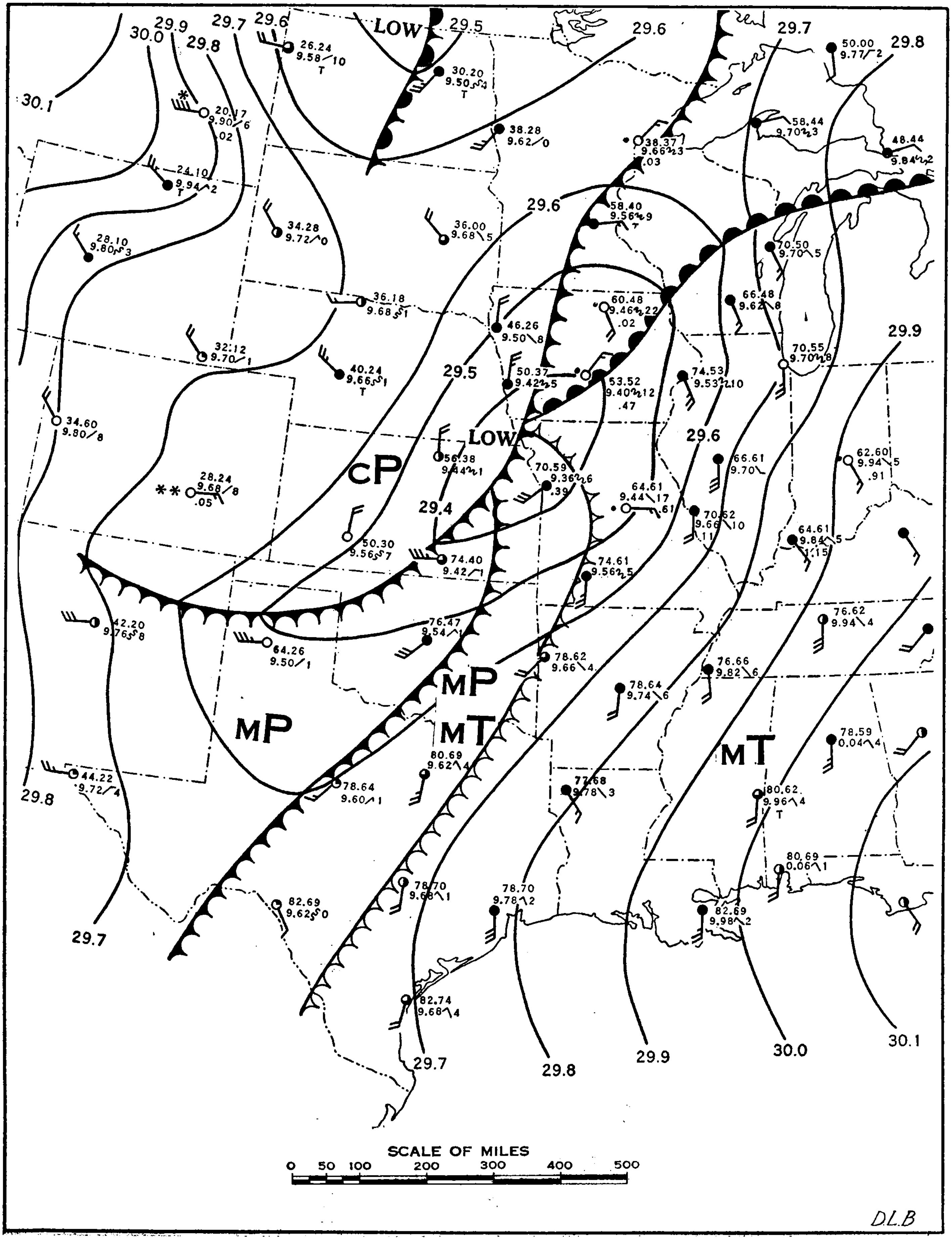

FIGURE 8.—Surface synoptic conditions, March 30, 1938, at 12:30 p. m., C. S. T.

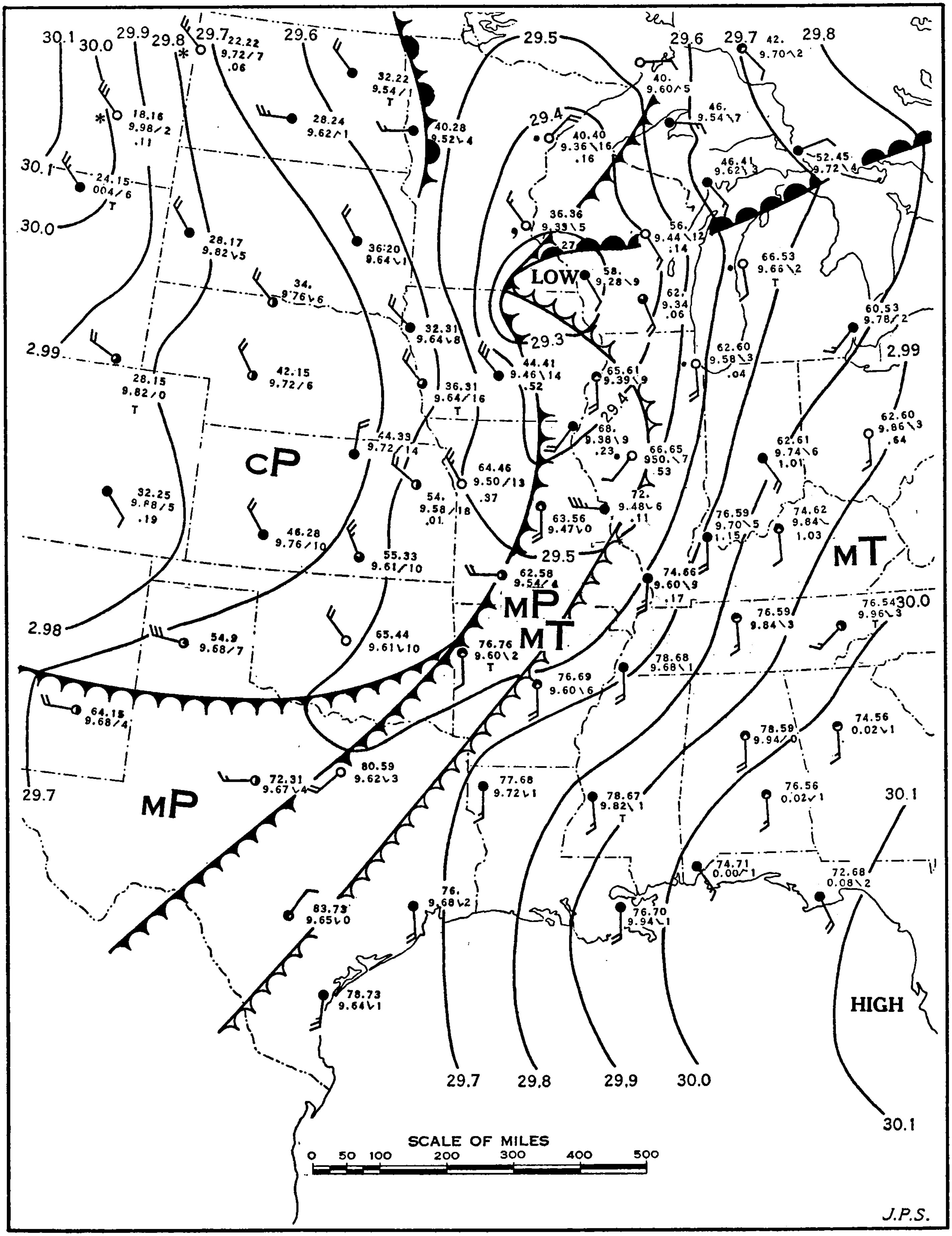

Figure 9.—Surface synoptic conditions, March 30, 1938, at 6:30 p. m., C. S. T.

ably colder than the Marine Tropical mass that it is displacing.

From the foregoing, and from close observation and study of many other weather situations in connection with which tornadoes have occurred, the writer has drawn the following conclusions:

1. Tornadoes appear to occur only in connection with upper-air cold fronts. These upper-air cold fronts may be of either of two types: (1) The conventional type caused by the interaction of Marine polar and Marine Tropical air masses; or (2) the precipitation-induced type, or pre-cold-frontal squall line [1], caused by the interaction of a precipitation-cooled mass of air with a Marine

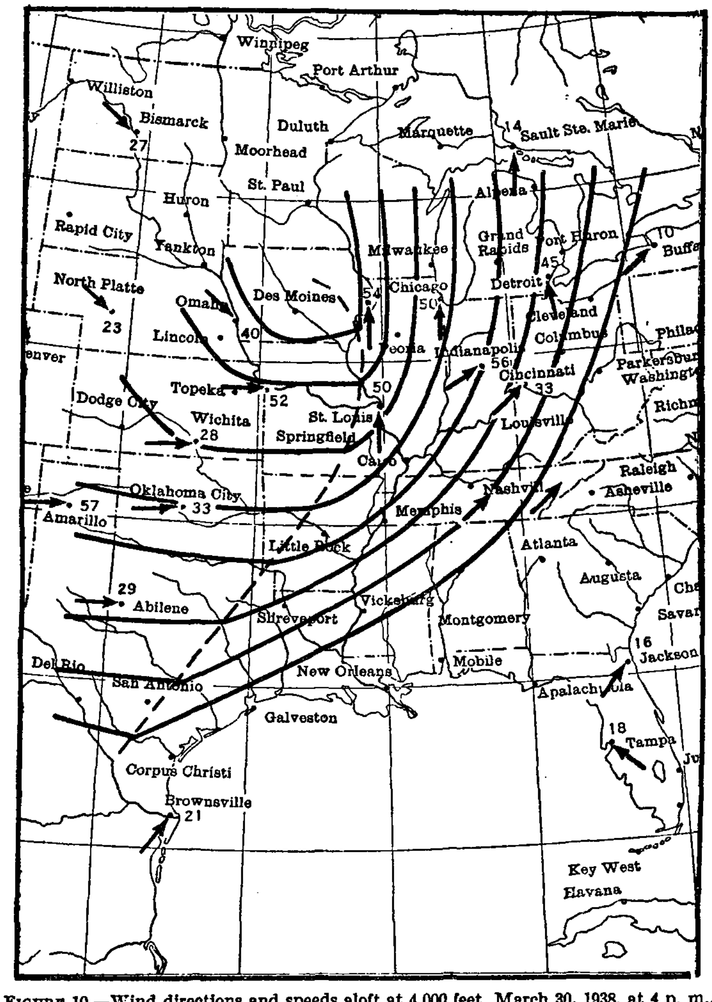

FIGURE 10.—Wind directions and speeds aloft at 4,000 feet, March 30, 1938, at 4 p. m., C. S. T. Broken line indicates approximate position of upper-air cold front.

Tropical air mass. The latter type always occurs in connection with thunderstorms which appear to be set up in connection with pre-cold-frontal horizontal convergence in a Marine Tropical air mass. The rain and hail that occur in the thunderstorms generated in the pre-cold-frontal zone cool the air through which they fall, particularly in the upper and middle levels, to considerably below the temperature of the air in the Marine Tropical air mass ahead, where no precipitation has yet occurred. There is thus built up a mass of denser air aloft that usually moves along rapidly, developing a squall line that exhibits most of the characteristics of a true air mass upper-air cold front, often causing violent thunderstorms and an occasional tornado. A marked characteristic of these precipitation-induced or "squall line" upper-air

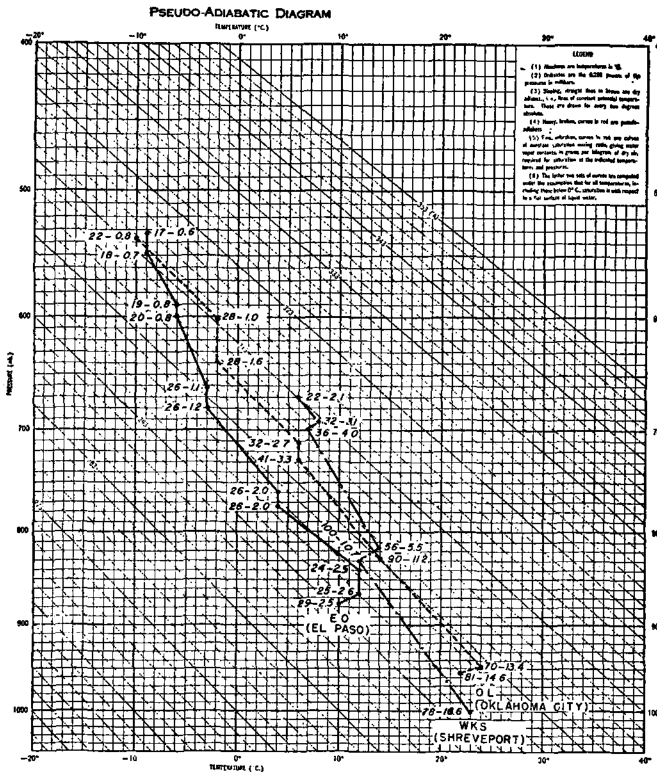

FIGURE 11.—Upper-air soundings from El Paso, Oklahoma City and Shreveport, March 30, 1938, at 3:00 a. m., C. S. T.

cold fronts is that they dissipate in a few hours, whereas the true upper-air cold front usually persists for several hours. Tornadoes that occur in connection with true mass upper-

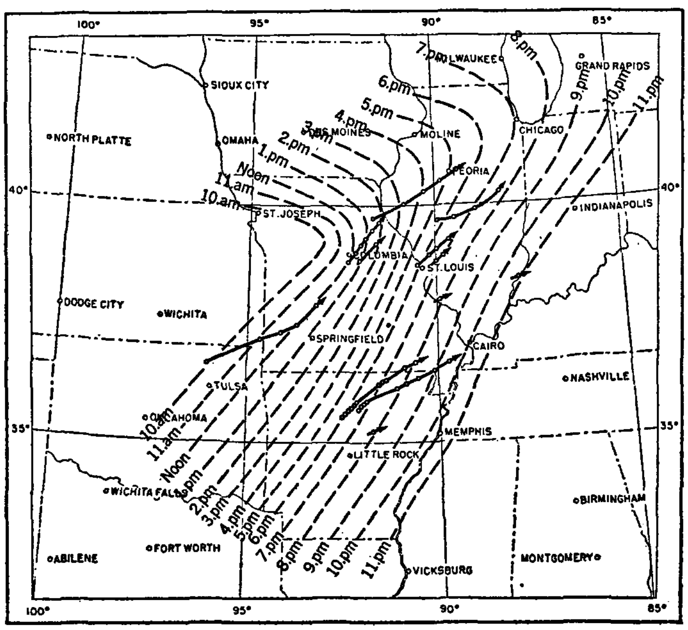

FIGURE 12.—Development and progression of tornadoes on upper-air cold front, March 30, 1938, C. S. T.

air cold fronts usually occur in groups or families numbering anywhere from 2 or 3 to as many as 12 or 15 in connection with a single front; while tornadoes that occur

[1] H. T. Harrison and W. K. Orrendorf on the "Pre-Coldfrontal Squall Line" in Meteorological Circular No. 16 of the U. A. L. T. C. Meteorology Department, March 1, 1941.

in connection with precipitation-induced cold fronts, or pre-cold-frontal squall lines, usually occur singly or occasionally in pairs.

2. Tornadoes occur by far most frequently in the surface warm sector of the cyclone; but they may occasionally occur even north of the center of the cyclone, and even in the surface cold sector of the LOW, as in the case of the tornado at McPaul, Iowa, on March 15, 1938, which moved from southeast to northwest.

3. Tornadoes form on cold fronts aloft, remain on the upper-air cold front throughout their existence, and move

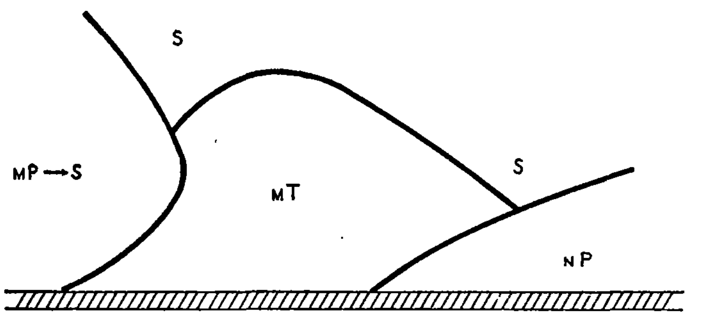

FIGURE 13.—Cross section of air-mass setup favorable for development of tornadoes.

up the front with approximately the speed of the wind in the warm air mass immediately ahead of the front, which usually blows approximately parallel to this front. In other words, the direction and speed of movement of the tornado is represented, to a first approximation at least, by the resultant of the direction and speed of movement of the front (or the wind component pushing the upper-air cold front along) and the direction and speed of the wind immediately ahead of the upper-air cold front, as shown in figure 14. The heavy curved line in figure 14A indicates the usual relative position of a cold front aloft in the great central valleys, with winds behind the

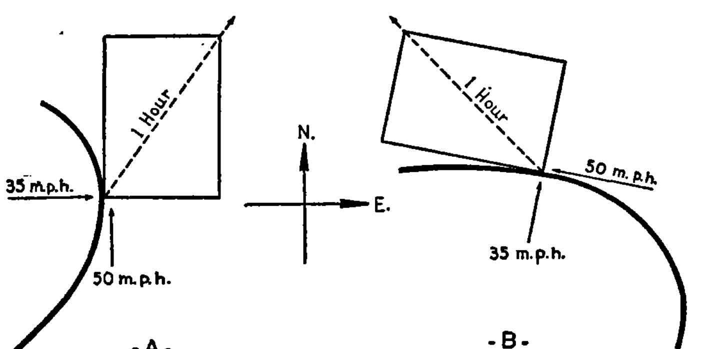

FIGURE 14.—Determination of the rate and direction of motion of a tornado: (A), the usual conditions, resulting in a trajectory from southwest to northeast; (B), the conditions resulting in the exceptional McPaul tornado.

front blowing from the west, and winds ahead of the front blowing from the south, always resulting in a tornado trajectory from southwest to northeast. The heavy curved line in figure 14B indicates the relative position of the cold front aloft that occurred in connection with the McPaul, Iowa, tornado. The converging winds from the south-southwest behind the front and from the east-southeast winds ahead of the front resulted in a tornado trajectory from southeast to northwest. The winds in the colder air mass behind the upper air cold front may flow approximately normal to the front, or almost parallel to it over a portion of the front, but the winds in the warm-air mass ahead of the front on which a tornado will develop usually flow approximately parallel to the upper air cold front along a considerable length of the front.

4. The lapse rate in the cold Marine Polar air mass to the westward of the warm, moist Marine Tropical mass is about the same as the lapse rate in the Marine Tropical mass to the eastward, and has about the same temperature up to some 1½ kilometers, above which the lapse rate is considerably steeper in the Marine Polar mass than in the Marine Tropical mass to the eastward. During the day the Polar mass, which has really become a Superior mass due to subsidence, becomes warmer in its lower levels up to 3,000 or 4,000 feet than the Marine Tropical air mass ahead of it. Above the level where the lapse rate in the Marine Polar mass begins to steepen sharply, the air becomes increasingly colder than the Marine Tropical air ahead of it, usually being much colder in the higher levels. This colder air from the intermediate and upper levels in the Marine Polar mass is usually dry, and flows out over and above the lower portion of the Marine Tropical mass; cutting off the top portion and lifting it very rapidly, due to the steepness of the cold front aloft; and violent thunderstorms and occasional tornadoes develop where vertical convection is strong enough. Such thunderstorm and tornadic action dies out abruptly as soon as the cold front aloft has "cut the top" off the dome of Marine Tropical air and has entered the mass of dry Superior air that usually lies to the eastward of the Marine Tropical air in such cases.

5. The seasonal migration of tornadoes from the deep South in the late winter and early spring to the Canadian border in midsummer is due to the fact that the Marine Polar masses from the Pacific become too warm aloft in the southerly latitudes for the production of upper-air cold fronts; such upper-air cold fronts form farther and farther north as the season progresses, causing tornadoes to migrate slowly northward as the season advances. This migration moves back southward again in autumn, as evidenced by the fact that tornadoes occasionally occur in autumn in the Mississippi Valley. However, such tornadoes in autumn occur only infrequently, probably because the Marine Polar masses at that season of the year are usually too warm aloft for the production of overrunning upper-air cold fronts—i. e., they do not, except occasionally, have lapse rates at middle and upper levels that are steep enough, compared with the lapse rates in the adjacent Marine Tropical masses to the eastward, to form a cold front aloft that in overflowing the lower layers of the Marine Tropical masses "clips off" their tops and sets up violent thunderstorm or tornado action. It appears that a steep lapse rate aloft in the Marine Polar mass is an absolute necessity for the production of tornadoes of the group or family type and that they occur only in connection with Marine Polar cold fronts. The writer has yet to find a tornado of the group or family type that has been caused by the interaction of Continental Polar and Marine Tropical air masses.

6. The rotation of the winds in the funnel cloud of the tornado must always be counterclockwise in the Northern Hemisphere, not due to the fact that the rotation of the earth prevents tornado vortices from whirling clockwise (since the vortices of waterspouts and dust whirls may whirl either clockwise or counterclockwise), but due to the fact that the movement of the air in the Marine Tropical masses in the Northern Hemisphere is always from a southerly direction, and to the right of the Marine Polar masses from the eastern sides of which the upper-air cold fronts originate and in which the air movement is usually from a westerly quarter.

Under these conditions, the southeasterly components of the southerly winds in the Marine Tropical masses interact with the northwesterly components of the westerly winds in the Marine Polar masses, to form vortices that necessarily must always have counterclockwise motion, as shown in figure 15A. Another way in which it is thought that tornado vortices may be—and, in the writer's judgment, perhaps usually are—formed is shown in figure 15B. Here, as the winds from the west in the Marine Tropical air mass approach the cold front they are slowed down considerably and deflected to the left, due to frictional drag as they come in contact with the wall of Marine Tropical air that is moving rapidly from a southerly direction. The winds in the Tropical air mass immediately in advance of the cold front usually move with higher speed, due to pre-cold frontal convergence, than do the westerly winds in the Polar mass converging on the front. The Marine Polar air would then flow alongside and adjacent to the edge of the Marine Tropical air mass, and in the same direction as the flow of the Marine Tropical mass, at a speed considerably less than the northward speed of the Tropical air. Swirls would therefore develop at points along the interface between the two air masses, and where these swirls occurred in connection with the rapidly ascending air currents on the edge of the Marine Tropical mass, tornado vortices could easily be set up.

Similarly, the winds in tornadoes that occur in the Southern Hemisphere always have clockwise motion.

7. The violence of the tornado will depend largely upon three factors: (1) The strength of the opposing winds immediately behind and immediately ahead of the front which set up the whirl around the vortex, (2) the area and degree of saturation of the uprushing mass of Marine Tropical air that is disturbed by strong local convection on the cold front aloft, and which is acted on by the opposing frontal winds to induce the spiral, upward counterclockwise motion in the funnel cloud; and (3) the steepness of the cold front aloft.

It is believed that these conclusions provide a sound basis on which the trajectories and speed of movement of tornadoes can be forecast *once they have been formed.* If, for example, a dense network of tornado-reporting stations were organized, by which a large percentage of the tornadoes that occur during daylight hours could be observed and reported immediately by telephone to a forecast district center in the area, it would be possible to forecast the approximate trajectory and speed of movement of a tornado, once it had been observed. Warning could be given of the approach of tornadoes and severe squall line thunderstorms only for periods of 15 or 20 minutes to perhaps 2 or 3 hours in advance; but commercial air-line operators and other interests vitally interested in such storms, and the general public would profit to that extent.

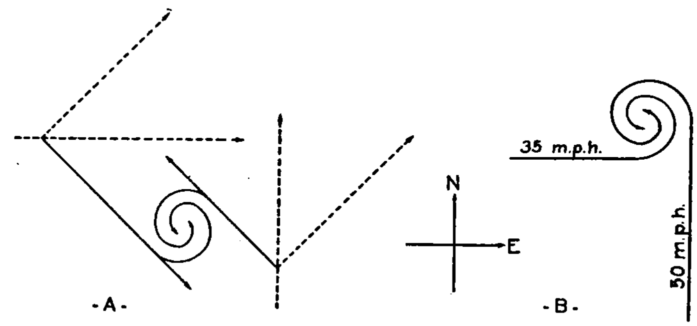

Figure 15.—Illustration of theoretical concept of development of tornado vortices.

METEOROLOGICAL AND CLIMATOLOGICAL DATA FOR APRIL 1942

[Climate and Crop Weather Division, J. B. Kincer, in charge]

AEROLOGICAL OBSERVATIONS

Table 1.—*Mean free-air barometric pressure in millibars, temperature in degrees centigrade, and relative humidities in percent, obtained by airplanes and radiosondes during April 1942*

Altitude (meters) m. s. l.	Stations with elevations in meters above sea level																											
	Albuquerque, N. Mex. (1,620 m.)				Atlanta, Ga. (300 m.)				Bismarck, N. Dak. (505 m.)				Boise, Idaho. (864 m.)				Brownsville, Tex. (6 m.)				Buffalo, N. Y. (221 m.)				Charleston, S. C. (14 m.)			
	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity
Surface	30	834	12.9	45	30	984	15.9	57	30	953	7.3	73	30	911	10.9	60	30	1,013	21.8	84	30	991	7.7	72	30	1,018	14.9	84
500	----	----	----	----	30	962	17.6	51	----	----	----	----	----	----	----	----	30	956	19.4	82	30	959	9.8	65	30	962	17.1	60
1,000	----	----	----	----	30	907	14.4	50	30	898	7.3	66	30	897	12.1	56	30	903	18.0	65	30	902	7.5	63	30	907	14.1	55
1,500	----	----	----	----	30	854	11.6	48	30	844	5.3	63	30	844	9.8	54	30	852	16.8	56	30	849	4.8	66	29	854	10.9	52
2,000	30	797	12.0	45	30	804	8.7	48	30	794	3.5	62	30	795	5.8	55	30	802	15.2	46	30	798	2.1	68	29	804	7.7	50
2,500	30	750	8.4	45	30	757	5.8	48	30	746	1.1	62	30	747	1.7	60	30	756	13.0	37	30	750	−0.7	68	29	757	5.4	49
3,000	30	706	4.4	48	30	712	2.7	46	30	701	−1.5	60	30	702	−2.2	64	30	712	10.2	33	30	704	−3.2	66	29	712	2.7	45
4,000	30	623	−3.6	53	30	628	−3.1	40	29	618	−7.6	59	30	618	−9.2	66	30	631	3.7	33	30	620	−8.8	60	28	628	−3.3	41
5,000	28	548	−11.0	57	27	553	−9.5	35	29	543	−14.2	55	29	542	−15.9	64	28	557	−3.8	36	30	544	−15.0	54	28	553	−9.4	41
6,000	28	481	−17.8	54	27	485	−16.6	33	29	474	−21.3	53	29	474	−22.8	60	28	490	−11.2	39	30	476	−21.1	50	28	485	−16.4	39
7,000	27	420	−24.4	50	27	424	−23.7	32	28	413	−28.8	50	29	413	−29.7	59	27	430	−18.1	37	30	415	−28.6	48	28	424	−23.7	38
8,000	27	364	−32.0	48	27	369	−31.1	31	27	359	−36.4	49	29	358	−36.5	58	27	375	−25.0	35	30	360	−35.9	47	27	369	−31.0	37
9,000	26	316	−38.7	----	26	319	−38.6	30	27	310	−43.9	----	29	309	−43.6	----	26	326	−32.0	33	30	311	−43.0	----	27	320	−38.4	35
10,000	26	273	−45.5	----	25	276	−45.5	----	27	266	−51.2	----	29	266	−50.0	----	25	283	−39.2	----	30	267	−49.8	----	27	275	−45.5	----
11,000	24	235	−51.9	----	25	237	−51.4	----	26	228	−56.4	----	28	228	−55.7	----	25	244	−46.8	----	30	229	−55.0	----	27	238	−52.0	----
12,000	23	201	−56.3	----	23	203	−56.8	----	26	195	−59.4	----	28	194	−58.9	----	22	210	−54.1	----	30	196	−58.9	----	26	203	−56.5	----
13,000	20	171	−58.9	----	23	173	−59.7	----	25	166	−60.2	----	28	166	−59.3	----	19	179	−59.9	----	30	167	−60.4	----	26	173	−59.1	----
14,000	19	145	−59.8	----	22	147	−60.3	----	24	141	−57.8	----	26	141	−57.9	----	17	152	−64.1	----	28	142	−58.7	----	25	148	−60.0	----
15,000	19	124	−61.4	----	21	125	−61.6	----	21	120	−57.5	----	26	120	−57.3	----	17	129	−68.7	----	28	121	−58.4	----	23	126	−61.3	----
16,000	18	105	−62.0	----	18	106	−62.7	----	17	102	−57.8	----	23	103	−58.0	----	15	109	−71.4	----	26	103	−58.7	----	22	107	−62.6	----
17,000	15	89	−62.1	----	16	90	−63.2	----	10	87	−58.1	----	20	88	−58.0	----	11	92	−73.3	----	19	88	−58.8	----	16	91	−63.0	----
18,000	12	76	−61.3	----	7	77	−63.6	----	6	74	−58.0	----	10	75	−57.5	----	10	78	−73.1	----	8	75	−59.2	----	14	78	−62.2	----
19,000	10	64	−61.5	----	----	----	----	----	----	----	----	----	----	----	----	----	6	66	−70.1	----	----	----	----	----	6	66	−61.6	----